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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 109

Technical Evaluation Report on the 49th (A) Propulsion and Energetics Panel Specialists' Meeting on Secondary Flows in Turbomachines

by

K.Papailiou

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TECHNICAL EVALUATION REPORT

on the [redacted] (A)

PROPULSION AND ENERGETICS PANEL SPECIALISTS' MEETING (1977)

on

SECONDARY FLOWS IN TURBOMACHINES ,

by D.

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TECHNICAL EVALUATION MEMORANDUM

This meeting was aimed to survey the present knowledge and physical understanding of those parts of the flow field in turbomachines that are subjected to high viscous stresses and vortices e.g. the flow close to inner and outer walls of compressors and turbines, within corners and near gaps as to be found at the hub and tip of the blades.

A comprehensive approach was achieved taking into account the theoretical and experimental status as well as surveying the advanced measuring techniques. Present demands of industry and offers of research workers to meet them emerged from discussions after each paper and from the extensive round table session.

It was made clear:

- why industry could not use the theoretical models available in the literature so far,
- that industry has a need for a theoretical estimation of the blockage factor to improve calculation of the low-loss core-flow
- that industry needs formulas for correct loss estimation.

As regards compressors, it is expected that simplified secondary vorticity considerations and pseudo-boundary layer approaches will result in further progress if they are backed up by experimental results.

For turbines, a different approach was suggested: fully three-dimensional calculation methods are expected to be necessary. They are admittedly time consuming but should be less expensive than experiments.

To develop the necessary flow models, new experimental techniques (optical) must be used. They are considered to be costly and complicated, thus experiments should be planned carefully. Emphasis will have to be placed on multistage flows, tip clearance effects and on radial machines.

The Panel has been asked by key participants to consider the coordination of future work (with respect to experiments) and to reconvene participants when new theoretical and experimental results are available (say, in five years).

TECHNICAL EVALUATION REPORT

by

K.D.Papailiou

1. INTRODUCTION

Improvement of the theoretical calculation of the inviscid core of the high performance turbomachines makes more and more necessary the better understanding of the secondary flows, i.e. the part of the flow field that is close to the inner or the outer walls and is therefore subjected to high viscous stresses as well as to the effect of the vortices induced by the blade-casing junction.

Such problems have been frequently discussed during various technical meetings but the Specialists Meeting held during the 49th AGARD Propulsion and Energetics Panel Meeting at The Hague, Netherlands, 28-30 March 1977, is the first international congress entirely devoted to this subject.

The meeting was divided into four sessions – a total of fifteen invited papers and seven short presentations – followed by a round table discussion.

2. CONTENT OF THE MEETING

A review paper by J.Horlock (Salford University, U.K.) summarized the earlier work on secondary flows in turbomachines. The secondary flow effects in compressors and turbines are very different:

- Compressor bladings give small deflections, and the relative motion between the blading and the wall is such that the secondary vorticity can be calculated by means of simplified methods and the estimation of boundary layer effects can be based on integral methods;
- Turbine blades induce large deflections and the relative motion is such that the three-dimensional effects are predominant. Complete flow calculations are required;
- Correct loss prediction methods useful for engine manufacturers do not exist for either compressor or turbine.

From the presentations made during the Specialists Meeting several tendencies for the development of theoretical research can be distinguished:

- As shown by J.Horlock, the followers of W.R.Hawthorne investigate the detail of the structure of the secondary flow field. Renewed interest in this field of research is manifested in the so-called Beltrami flows in which total pressure is constant and vorticity components exist parallel to the local velocity;
- A slightly different method was presented by H.Marsh (University of Durham, U.K.) who emphasizes the role of the time lag between pressure side and suction side flows to approximate estimation of the different components of the secondary vorticity;
- An alternate way was followed by the research team of the Ecole Centrale de Lyon, F., G.Bois, F.Leboeuf, A.Comte, K.Papailiou. By means of generalizing the classical boundary layer methods, they estimate the overall effect of the secondary flows. Apparently such an approach is very satisfactory even in the transonic range. The junction between the inviscid or at least the low loss flow region and the secondary flow region is made on the basis of static pressure compatibility. An experimental paper given by the same team showed the validity of this approach that may be considered as a first step towards the estimation of losses and blockage factors due to the development of wall boundary layers amplified by the secondary effects.

For higher Mach numbers, namely in the case of supersonic compressors all these approaches become irrelevant and Fruehauf, University of Stuttgart, Ge., gave some preliminary results of flow calculations.in compressors using the characteristics method.

Outside of these theoretical papers, most of the presentations described experimental results. The techniques included probe surveys, laser velocimetry, and several forms of flow visualization.

Results obtained by advanced methods were presented:

- hot wire anemometry in a subsonic compressor (Ch. Hirsch, Free University of Brussels, B.),
- detailed boundary layer measurements near the casing wall of another subsonic compressor (W.Kümmel, Technisch Hochschule, Aachen, Ge.),
- laser anemometry in a transonic compressor (H.Weyer, DFVLR, Köln Wahn, Ge.),
- turbine flow analysis using advanced theoretical methods (W.Tall, Wright-Patterson AFB, in the United States) and multistage turbine experiments (B.Barry, Rolls Royce 1971 Ltd. in the United Kingdom).

Due to the difficulties encountered in measurement in actual turbomachines, some presentations were restricted to laboratory tests. The study of the flow distortion in an annular blade cascade by J.Huard, ONERA, F., showed all the complexity of distorted flows in a three-dimensional test facility: the streamlines undergo inwards or outwards radial shifts according to their total pressure.

Using a moving belt at one wall of his linear blade cascade, H.B.Carrick, I.C.I., U.K., analyzed the effect on the secondary phenomena in the cascade of a skewed boundary layer in which the velocity is not parallel to the main flow velocity. This test set-up simulates in a laboratory the test conditions at the entrance of an actual compressor.

In a similar way, L.Goldman, NASA, Lewis Research Center, U.S., simulates the effect of endwall cooling air injection on the performance of an annular cascade of turbine blades, and Ph.Marchal and C.Sieverding, Von Kármán Institute, B., analyzed the structure and the loss repartition in the endwall zone of a linear low speed turbine blade cascade.

No new loss correlations were extracted from all these measurements, although it was understood that secondary flows lead to high losses and a good understanding of them is necessary to improve turbomachine performances. In order to decrease these losses some devices were proposed.

Wall boundary layer suction was proposed by both B.A.Gustafson (Chalmers University, Sweden) who uses porous walls and G.Meauze, ONERA, F., who eliminates the blade cascade end wall boundary layer through slots positioned near the blade channel minimum section. In both cases improvement of the flow field and reduction of the secondary losses were obtained. No overall balance taking into account the work necessary for boundary layer suction has been presented in either case.

A new blade surface treatment was proposed by M.P.Boyce, Texas A. & M. University, U.S. Axial grooves on the blade suction surface were reported to delay the stall phenomenon.

A proposal by J.Renken (DFVLR, Ge) to smooth out the blade-casing wall junction in order to diminish the secondary losses was disapproved, since some compressor tests reported by J.Horlock showed no efficiency improvements.

3. ROUND TABLE ON THE NEEDS OF ENGINE MANUFACTURERS OF SECONDARY FLOW KNOWLEDGE AND THE CONTRIBUTION OF THE PRESENT AGARD MEETING TO THIS KNOWLEDGE

A better knowledge of the flow field in the wall region and a correct estimation of secondary losses are of paramount interest to engine manufacturers, according to R.Bouillet, SNECMA, F. A better knowledge of secondary effects is required for the following reasons:

- secondary flows affect the engine efficiency: in some cases such as high pressure turbine stages, the secondary losses account for half of the stage losses,
- secondary flows modify the main stream both through the channel blockage and the pressure equilibrium condition,
- a better knowledge of the blockage factor and the inviscid flow calculation leads to a better blade setting.

A typical example of the effect of secondary flows on compressor design is the case of a seven stage axial compressor that has large secondary losses due to high pressure gradients and an eight stage compressor designed for the same performances that has higher efficiencies.

Reduction of secondary losses by complex methods such as casing boundary layer suction, grooves or any other casing treatment, reduction of peripheral gaps using abradable materials is not a final solution. The stall margin may be extended but the efficiency is generally decreased.

The use of correct secondary flow models and correct loss predictions at the engine design stage is the preferred way to minimize the effect of secondary flows.

By summarizing earlier work and presenting recent analytical researches the present AGARD meeting gives already part of the answers to these questions. That is how J.Chauvin, Von Kármán Institute, B., evaluates the contribution of this meeting to the progress in secondary flow research. For compressors almost all the necessary tools are in the hands of engine designers. For turbines, the development of fully three-dimensional calculations still seems necessary.

The simple loss and blockage factor correlations the engine manufacturers use now lack generality and it will be necessary for them to learn to use the new theoretical models proposed by research people. On the other hand, if the theoreticians wish to improve their models, they have to take advantage of all the advanced experimental data presently available. The empirical factors that still exist in the best formulas can be estimated more correctly in that way.

This approach could refine the theoretical methods that are already available and seem to fit correctly the compressor data. For turbine flows the complete three-dimensional theory has to be developed. But in an ultimate stage these three-dimensional calculations may replace costly experimentations.

For D.Eckardt, DFVLR, Köln-Wahn, Ge., the lack of experimental results on secondary flow in actual turbomachines is one of the difficulties in building three-dimensional models. The hot wire anemometer that has been widely used in low speed compressors should be more and more replaced by laser anemometry. Measurements closer to the wall become possible with the use of the fluorescent technique.

P.Runstadler, CREARE Corp., U.S., agreed on this point. He emphasized the role of correctly planned flow visualization that may be a great help for theoreticians to build a model. The main difficulty in flow visualization comes from the unsteady effects. The most promising techniques are:

- sheet of light
- laser holography
- wall trace

From the general discussion that followed these comments made by the round table leaders, this summary can be given:

Everyone agreed that the engine manufacturers were reluctant to use the present day theories (with some exceptions), feeling that they were not developed enough to provide useful information. It was observed, however, that not enough cases had been treated in order to decide whether or not these theories could be of some use.

As far as the state of the art is concerned, it was generally agreed that boundary layer type methods helped by the simplified inviscid flow theories (as developed by Hawthorne, Horlock, Lakshminarayana and Marsh) could provide a sound basis for annulus wall viscous layer prediction for compressors at design and off design conditions. There is a lack of information, however, as far as the last stages of multistage compressors are concerned and as far as tip clearance effects are concerned.

The turbine secondary flow physics are quite different because of the effect of secondary vorticity on the boundary layer and so fully three-dimensional calculation methods ought to be used.

These could seem quite expensive and difficult, but recent advances in computers make them more accessible.

All agreed that progress in experimental techniques helped the understanding of flow phenomena and that they ought to be used regardless of the costs.

J.Horlock pleaded for carefully planned experiments. He seemed to imply that it was not yet possible to use the full equations and that the simplified models used should come from the experimental results.

Figure 1 summarizes the content of the meeting.

4. CONCLUSION AND EVALUATION OF THE MEETING

The massive participation – over 120 attendees for a meeting on such a specialized subject as "Secondary flows in turbomachines" – shows the importance and timely nature of the subject chosen by the AGARD Propulsion and Energetics Panel for its 49th meeting.

Most of the fifteen invited papers and the seven short presentations made during the meeting came from research organizations with only a few papers presented by industry. It is unfortunate that a more complete representation of industry could not be obtained, but most of the main engine manufacturers were represented.

The discussion periods were generally very lively. The representatives from industry made clear:

- why up to now they were not able to use the theoretical approaches available in the literature,
- the need for a theoretical estimation of the blockage factor to help them to calculate more correctly the low-loss core of the flow,
- the need for correct loss estimation formulas.

The response from research workers suggested:

- simplified secondary vorticity considerations and pseudo-boundary layer approaches seem to be promising for multistage compressor analysis if backed by experimental results,
- this analysis seems to be inadequate for turbines and fully three-dimensional calculation methods must be used. These are still time consuming but are certainly less expensive than experiments,

- new experimental techniques must be used, in spite of cost and effort, to provide the necessary flow models. However, experiments must be carefully planned,
- lack of understanding and experimental information exists in the following areas:

(i) multistage environment
(ii) tip clearance effects
(iii) radial machines

The attendees were unanimous in recommending that the same subject be considered for a future AGARD Specialists Meeting when new theoretical and experimental results are again available.

	No.	AUTHORS	THEORETICAL	EXPERIMENTAL	COMPRESSOR	TURBINE	SINGLE STAGE	MULTISTAGE	CASCADE (Plane of annular)	AXIAL	RADIAL	OPTIMIZATION	HIGH SPEED	LOW SPEED
PRESENTATION	(x)													
	2	LEBOEUF – COMTE – PAPAILIOU	•		•			•		•			•	
	3	BOIS – LEBOEUF – COMTE – PAPAILIOU		•	•		•			•			•	
	4	GALLUS – KUMMEL	•	•	•	•	•			•		•	•	
	5	BOYCE		•	•		•			•		•		•
	6	HUARD		•	•				•	•			•	
	7	DE RUYCK – HIRSCH – KOOL		•	•		•			•				•
	8	WEYER – DUNKER		•	•					•			•	
	9	CARRICK	•	•		•			•	•				•
	10	MEAUZE		•	•				•	•		•	•	
	11	MARCHAL – SIEVERDING		•		•			•	•				•
	12	HEINEMANN		•		•			•	•			•	
	13	GLYNN – SPURR – MARSH	•			•			•	•				•
	14	TALL	•	•		•	•			•		•	•	
	15	GOLDMAN – McLALLIN		•		•			•	•		•		
SHORT TALKS	16	BUSSI – PANDOLFI	•						•					•
	17	BARRY		•		•		•		•			•	
	18	ECKARDT – KRAIN		•	•		•				•		•	
	19	GUSTAVSON		•	•				•	•		•		•
	20	FRUEHAUF	•		•		•			•			•	
	21	RENKEN	•	•	•				•	•				•
	22	RAILLY	•											

Figure 1

(x) Paper 1, the introductory lecture by Professor Horlock is not considered in this list.

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21. Railly, J.W. — *Note on Relative Vorticity*

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14. Abstract

This Technical Evaluation Report on the 49th (A) PEP Specialists' Meeting on "Secondary Flows in Turbomachines" contains a critical survey of the 15 papers presented, on the informal presentations and on the extended Round Table Discussion. Conclusions are drawn, areas with high priority interest are marked and solutions both for compressor and turbine flows are suggested.

The papers presented at the meeting together with the discussions, the informal contributions and the Round Table Session are published as AGARD Conference Proceedings CP 214 "Secondary Flows in Turbomachines".

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